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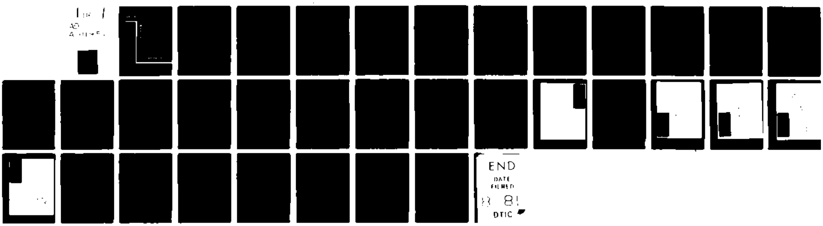

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AIR FORCE HUMAN RESOURCES LABORATORY

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FLIGHT SIMULATOR:
USE OF SPACEGRAPH DISPLAY IN AN INSTRUCTOR/OPERATOR STATION

By

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Final Report

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AIR FORCE SYSTEMS COMMAND
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NOTICE

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This technical report has been reviewed and is approved for publication.

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SpaceGraph is described as a new computer-driven display technology capable of showing space-filling images, i.e., images that are truly three-dimensional. This report details the findings on how this new technology can be used in, and in conjunction with, the Instructor/Operator Station (IOS) of a flight simulator.

In current practice, the location, altitude, and flight attitude of a simulated aircraft are graphically shown to the instructor/operator on flat screens. This dimensionally-mismatched form of data presentation creates a greater workload on the instructor/operator who must integrate several flat presentations into a mental construct of performance in three-dimensional space. Such space-filling data should be shown with a space-filling display, now that one exists.

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Item 20 Continued:

Unexpectedly, student pilots were also able to use the display directly. As a training aid intermediate between "flying" one's hands in the classroom and "flying" the big simulators, it would appear to be a new kind of low-cost, part-task training vehicle. It offers the realism of computer-produced flight dynamics but with a view of the aircraft rather than out of the aircraft.

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CONTENTS

A

I. INTRODUCTION

SpaceGraph is a new computer-driven display technology capable of showing space-filling images, i.e., true three-dimensional. The instructor/operator station (IOS) of a modern flight simulator has severe display problems arising from the complexity of the simulation system and its actions. This report details our findings on how the new display resource of SpaceGraph can be used in the IOS.

Simply put, despite differences, all IOSs share one common display need: the current position and velocity of their simulated aircraft in three-dimensional space. Inherently continuous (as opposed to discrete) and time varying, these data are also spatial. Yet they are shown to the instructor/operator on flat screens, a form of presentation dimensionally mismatched to the data. This mismatch creates a greater workload on the instructor/operator through its inescapable awkwardness.

We conclude that space-filling data should be shown with a space-filling display. Awkwardness would change to naturalness. The demand on the instructor/operator to integrate disparate flat presentations into a mental construct of performance in three-dimensional space and then to criticize such performance would be replaced with an intuitive presentation allowing immediate criticism.

Beyond the explicit goals of the contract, we have also observed that part of the training functions now carried on in the classroom and in the simulator could instead be done with a space-filling display which gives an outside-in view of one or more aircraft. The apparent benefit is decreased training cost and time.

SpaceGraph embodies a new technology in computer-driven displays. Using a novel form of time-varying, very-wide-field-of-view optics, the technology provides all of the virtues of interactive computer graphics but with images that are space-filling. Images appear in a display volume, not on a display surface. Further details on this visually dramatic technology are presented in the appendix.

Regarding SpaceGraph as a new display resource, it is natural to seek sites and applications for it which are now not well served by flat displays. One such site is the instructor/operator station of a modern flight simulator. There the instructor and the operator of the simulator (the instructor sometimes may also be the operator) face a panoramic array of instrument dials and cathode ray tubes (CRTs), the totality of which hopefully keeps them informed about trainee performance. The purpose of this effort was to find ways at the IOS in which SpaceGraph could reduce the instructor/operator's workload.

The central thrust in this contract, as originally conceived, was to match the information display *needs* of the IOS to the information display *attributes* of SpaceGraph. The needs were to be derived from the results of a previous Air Force Human Resources contract. The attributes were not only to be cataloged but were to be enhanced in several ways likely-- as then judged -- to improve the match of needs to

attributes. As time passed, however, for a variety of reasons, the list of needs was not made available in a useable form. We therefore took a less structured, more pragmatic approach: We observed actions at two IOSs to see first hand what problems SpaceGraph might ameliorate. We then erected sample images directed at those IOS problems.

Despite these contractor-approved deviations from the originally proposed methodology, the effort has produced results more immediately applicable to current IOS problems — and to other facets of pilot training — than we expected. SpaceGraph, by showing an outside-in view in true 3-D of one or more aircraft, opens up a major new training vehicle. It bridges the gap between the outside-in view of hand flying in the classroom and the inside-out view of simulator flying.

II. IOS NEEDS AND SPACEGRAPH CAPABILITIES

IOS Needs

We were able to ascertain some needs, by first-hand observation, at three IOSs: one at the SAAC* at Luke AFB and one each at the ASPT** and at the undergraduate pilot training facility at Williams AFB. After two days of observing, one simplistic observation emerged as paramount: Flying is intensively three-dimensional, yet *none* of the instructor's displays was other than flat. The instructors were mentally integrating the information from multiple displays, their mental constructs acting as surrogates for the display they did not have — i.e., an outside-in view of the student's plane in 3-space.

When displays are mismatched to the information to be conveyed, the inevitable results are a proliferation of displays and a higher than necessary workload. In this case, say the ASPT, one IOS display showed the aircraft's position, while another showed its altitude versus one position coordinate. If no further information were necessary, there would already be two images showing four things, whereas the information content, considering the capabilities of the SpaceGraph display, justify only one image showing three things.

There are fundamental questions left unanswered: Should the instructor be able to criticize pilot performances using an error-measuring capability not available to the pilot? If the instructor uses displays not available to the pilot, can the instructor translate criticism into a form useful to the pilot? Would the student pilot benefit from seeing the instructor's displays in a replay debriefing? Our workscope led us to formulate such questions but did not begin to have the scope necessary to answer them in a formal way. Informally, however, it appeared to us that the needs of the instructor and those of the student are not cleanly separable.

Considering the large number of parameters monitored and displayed or displayable at the IOS, we expected at least several needs to be apparent to the instructors and/or operators. In conversations with at lease four IOS personnel, we found that not to be the case. Instructors and operators, presumably proficient at their IOS posts, had learned to cope and expressed satisfaction. Their jobs were obviously demanding but not, in their perception, too demanding. They did not express dissatisfaction with any aspect of IOS data display, believing, apparently, that since everything conceivable was displayed or displayable, they had no grounds for complaint.

Instructors' awareness of training needs in the classroom was a different story. Apparently hand flying is the primary display, and it

*Simulator for Air-to-Air Combat

**Advanced Simulator for Pilot Training

was deemed lacking in many ways. For example, it fails for formation flying, for turns and rolls not compatible with arm joints, and, in general, it results in a realism gap. (Notably missing from the deficiencies was the outside-in view it provides.)

We also discussed training needs during debriefing/replays. At the SAAC, students see a TV-like replay. Its flat presentation of a non-flat subject was deemed undesirable but the outside-in view was not. An important suggestion was made there (at Luke AFB) that an off-line display (i.e., one with stand-alone capability) of air-to-air combat could be used as a game in the lounge. Also suggested by the instructors we interviewed was a replay capability which could show a student's improvement over time.

SpaceGraph Capabilities

Unless specifically to the contrary, the following discussion refers to easily achieved capabilities of the generic technology pioneered by the current implementation, not to capabilities of the current implementation itself.

The appendix discusses in detail the modes of SpaceGraph operation: A, B, and C. (These modes were formerly referred to, respectively, as line mode, surface mode, and volume mode, a terminology which was potentially confusing.) Briefly, mode A is suited to draw space-filling images made of dots, lines and alpha-numerics. Mode B is best suited to draw space-filling images which can be thought of as landforms, i.e., vertical deformations of a horizontal plane. Mode C is best suited to draw space-filling images which can be thought of as cloudforms, i.e., 3-D scalar fields (which have a real numeric value at each lattice point (x, y, z) in the volume). In general, mode A has high spatial resolution for sparse images while mode C has low spatial resolution for nonsparse images. Mode B has some features of A and some of C. Mode A is clearly the mode of choice for depicting airplanes, coordinate reference frames, alphanumeric flight parameters, runway lights, data plots, and other sparse images which want high spatial resolution.

As a result of this contract, a new mode was implemented: overlay/underlay (O/U) mode. It is intended for creating mode A-like images in the front-most plane of the display volume, called overlays, and in the rear-most plane of the display volume, called underlays. The purpose is to expand the display's capability by taking advantage of the two otherwise useless times during each of the mirror's vibrating cycles when the mirror's velocity is zero.

As a second result of this contract, mode A was made operational during *both* halves of the mirror's sinusoidal cycle. This new capability immediately doubles the achievable complexity of images in mode A. However, exploration of its capability must await a new mirror, since the present one fails to achieve sufficiently perfect forestroke-backstroke symmetry. An improved mirror is being developed under other funding.

As a third result of this contract, a new means was designed and brought near to operational status whereby the viewer can easily direct a pulsed laser beam into the image for the dual purposes of pointing and of selecting light buttons.

Mixed mode operation is using the two halves of the mirror cycle in two different modes. An example of a mode A/mode B mix is an airplane in mode A flying over terrain in mode B. To this pair could be added an O/U-mode image of an altitude scale, or a wind shear diagram, or alphanumeric captions, instructions, or data.

Although SpaceGraph might reasonably be described as a true 3-D display, it is important to note that the three Ds referred to are only the spatial dimensions. Along with other CRT displays, SpaceGraph also has brightness and time variations as display resources. So it would not be unreasonable to describe SpaceGraph as a 5-D display and other conventional CRT displays as 4-D. No matter how described, however, SpaceGraph has one more dimension than conventional CRTs, and therein lies its unique capability.

The central goal of this contract is to find ways at the IOS for which SpaceGraph's unique capability can be advantageously exploited. It is tempting to restrict the search to the depiction of space-filling arrangements of objects and scenery. But to be more systematic, SpaceGraph's capability should be kept in mind: one more dimension. Therefore, applications now pursued on flat screens, e.g., plotting range versus fuel, can be extended, e.g., plotting range versus fuel versus altitude. In general, any one or more of SpaceGraph's five dimensions (x, y, z, brightness, time) can be used to plot a spatial (e.g., altitude) or a non-spatial (e.g., lb. of fuel) parameter. It is easily seen that the number of combinations of spatial and non-spatial parameters is very large, so new constraints can be usefully introduced. One such constraint is that a spatial parameter must be plotted by x, y, or z. Another, on the grounds of simple pragmatism, is that the image should embody its information content in an intuitive form. (It is possible to imagine plots which are very informative but only after a lengthy "acclimatization." It is more than possible to imagine such plots as successful in theory but ignored in practice.)

As a final observation on SpaceGraph's capabilities in general, we must not overlook the obvious: SpaceGraph can show aircraft realistically flying in 3-space, while flat presentations cannot. Since aircraft flying is the central subject, SpaceGraph's one added dimension could be the key to a whole new (additional) technology for flight training.

III. IDEAS AND TRIALS

Because the central task had a large element of brainstorming, we sought ideas from as many informed people as possible. Here follows a list of these ideas, in their raw form, organized chronologically by meeting number. Contributors at these meetings were Bolt Beranek and Newman Inc. staff members and consultants, Air Force personnel, and Singer-Link Simulator personnel. All contributors were qualified by virtue of being pilots, instructor pilots, supervisors of pilot training, researchers in pilot training, or experts in human factors as they relate to flying. The line items are numbered for later referencing:

<u>Ideas for ways to use a SpaceGraph display at (and in conjunction with) the IOS</u>

<u>Meeting #1</u>

1. Monitor heading, altitude, and airspeed together
2. Show landing approaches
3. Show interceptor tactics
4. Air-to-air refueling
5. Formation flying in global view (outside-in)
6. Remotely Piloted Vehicle (RPV)
7. Ground Controlled Approach
8. Performance analysis
9. Instrument/night air work and navigation.
10. Predictive displays like flying through Instrument Landing System gates
11. Coordinated maneuvers

<u>Meeting #2</u>

12. Flightpath analysis (plane represented as a point) with reference to:
    - airspace restrictions
    - speed restrictions
    - landing pattern
13. Parameter and parameter sets which would profit from a true 3-D representation:
    - airspeed
    - altitude
    - turn and slip
    - attitude
    - heading
    - Instrument Landing System (ILS) approach indications
    - Very-high-frequency Omnidirectional Range indications
    - climb and descent with rates of change
14. ILS gates with airplane and velocity vector

Meeting #3

15. Summary information not readily shown in a flat picture
16. Approach path taken
17. Aerobatics: velocities and accelerations
18. Landing maneuvers within the air space restrictions
19. Air-to-air combat
    Cannon orientations
20. History of flight track improvement

Meeting #4

21. Air-to-air combat
22. One plane flying relative to terrain
23. Landings
    Give instructor a variable viewpoint (outside-in) of landing
    Slow motion, "stop frame" capability

Meeting #5

24. Approach control geometry
    Desired location relative to actual location
    Predicted path
25. Parametric display of flight maneuvers, e.g., elevator (as x), rudder (as y), aileron (as z), simultaneously plotted at successive times

Meeting #6

26. Outside-in view instead of inside-out as a part-task trainer
27. Effects of wind in outside-in view
28. Gliding as a form of energy management
    Parameter displays showing relations of air speed, sink rate, glide ratio, time aloft, maximum range
29. Predictive displays for carrier approach and landing
30. Dogfight game theory
31. Terrain following

Meeting #7

32. Sets of displays as a training manual of maneuvers, correlated with control settings
33. Aerial combat with more than two aircraft — outside-in view
34. Energy maneuvering

Meeting #8

35. Energy management
36. ILS cone with aircraft (outside-in view)
37. Air refueling rendezvous and docking considerations

38. Airborne uses for true 3-D display
    View of own and other aircraft showing cone of weapons influence
    RPV
39. Terrain following
    Outside-in view of fixed plan over moving terrain
40. Gliding — vectors with impact prediction

Meeting #9

41. Enhancement to existing part-task trainers
    Compare performance to that required in basic tactical game skills
42. Replays of performances in real aircraft from telemetered data
    Performance analysis showing time versus critical task-dependent flight parameters

Meeting #10

43. History of student performance
44. Debriefing display for instructor and student, showing actual versus desired performance

Meeting #11

45. Replacement for current displays which show 3-D flightpaths with multiple 2-D views
46. Aid to teaching judgment by showing parametric data more pictorially, e.g., formation flying

Meeting #12

47. Lower-cost training device than T-37 or ASPT
48. Judgment training aid for Landing Signal Officers
49. Ordnance delivery
50. Energy management
51. Substitute for classroom hand-flying (outside-in view)
52. Many-plane interactions
    Combat tactics
    Formation flying
53. Replay/debriefing using data telemetered from actual aircraft

Meeting #13

54. Air-to-air combat (outside-in view)
    As game for practicing
    As aid for debriefing
    As pictorial presentation of usually digital data air speed, angle of attack, accelerations, altitude, control surface usage

55. Missile, cannon fire trajectories

56. Zoom-in outside-in viewing showing, with high pictorial resolution, the relative orientation and separation of air combatants when close

Meeting #14

57. Aid to instructor's judgment in showing better the student's control settings

58. Integrated displays showing aircraft plus control settings and energy information

Meeting #15

59. Replacement for hand flying in showing effects of wind
60. Predictive display for carrier landing
61. Training in tactical game theory
62. Training in terrain following

Meeting #16

63. Flying-manual augmentation by showing maneuver in real 3-space
64. Pattern analysis of errors in coordinated maneuvers
65. Airborne substitute for inside-out view under low visibility conditions
66. Energy management training aid
67. Outside-in view to show student pilots where they are in a specific maneuver

Meeting #17

68. Airborne radar imagery showing own plane and weapon cones
69. Airborne use particularly attractive for bombers
70. Terrain following for helicopters
71. Gliding
    Predictive displays
    Space shuttle landing trainer

This list conveys several new and important concepts:

1. Hand flying in the classroom gives an outside-in view while full-blown simulators give an inside-out view. There appears to be an enormous gap here, one in which a SpaceGraph display might be a remarkably attractive and cost-effective, outside-in, part-task training aid.

2. The IOS now is burdened with flat displays attempting to convey flightpath information. This information could be conveyed more simply and intuitively by a single true 3-D display. It is difficult to imagine a more perfect match between the needs at the IOS and the capabilities of the new display technology.

3. Review and debriefing following simulator flight sessions might be helped by an outside-in view, i.e., by giving the student off-line the same critical aids used on-line by the instructor.

Energy management was mentioned by three or four people as a topic needing better visual presentation. In order to better understand the subject, since no one we asked could give us a really clear exposition of it, we did a modest literature search. The result was that we now understand why it is both difficult to explain and important to understand. First, there seem to be two parts to energy management which are distinguished by whether or not the weight of fuel changes during the time period of interest. Thus, one part could be called (but it isn't) "long-term energy management" and the other "short-term energy management." Both subjects are treated theoretically in the literature in an academic style far removed from a flier's world of moment-by moment decision making. It would appear that pilots in training are exposed to these twin subjects academically in class and practically while flying, in the hope that the connection will become evident as experience accumulates. Our emerging view of this training problem is that to approach the extent that experienced pilots have learned the operationally useful energy management ideas from flying, student pilots can learn with an outside-in view of a flyable plane. In short, intuition can be trained with a part-task special purpose trainer.

Outside-in versus inside-out views emerged during these meetings as an important and fertile topic. There was much discussion over the extent to which flyers think of themselves as if from outside and behind their own plane. For if this outside-in mental construct is indeed an important aid in flying, the inside-out view of a simulator achieves realism at the expense of good teaching technique. A flat display is best suited to an inside-out view of a semi-infinite airspace, while a SpaceGraph display is better suited to an outside-in view of a finite piece of the world. So, it may be that SpaceGraph is very well matched to just that piece of pilot training not well served by conventional display technologies.

Of the many other interesting ideas contributed at these meetings, at least two deserve comment. First, the possible use of a SpaceGraph display in the training of Landing Signal Officers (LSOs) is tantalizing, since LSO training inherently requires an outside-in view (as from a carrier deck), LSOs must undergo a lengthy training period including much on-the-job training, top LSO performance is vital to expeditious and safe boarding of Navy fliers, and LSO training aids are almost nonexistent.

Second, the idea for a landing trainer for the Space Shuttle epitomizes the landing trainer problem: How can a pilot's reaction to a complex spatial problem be trained without endangering the pilot or the aircraft? An answer is certainly suggested by observing the naturalness with which a true 3-D display renders spatially complex data sets.

In order to expedite the creation of trial images, two new computer programs were created (they were beyond the proposed workscope). The first, called GDP (Geometric Description Processor), makes it possible to describe an object, like an airplane, with the primitive display elements of lines and dots and then to declare that the object is also a primitive. A new image can then be described as composed of lines, dots, and airplanes. The second new program, called PATHS (for paths in space), allows a smooth flightpath in space to be described by a series of connected straight line segments which the program then smooths with circular splines. The airspeed and turning radius of an aircraft can be specified along the path as thus defined, and the program will manage banking appropriately as well as display the aircraft at specified time increments. This multiple display of a single aircraft is in lieu of displaying a moving aircraft, which is not yet possible due to the early developmental state of the current system.

Since we were directly exposed to the IOSs at the ASPT and at the SAAC, we concentrated on ways to use a SpaceGraph display at those sites. As already noted, each IOS attempts to display a three-dimensional aircraft position with one or two flat pictures.

In the photographs (Figures 1 to 6) which appear at the end of this report, it is crucial for understanding to realize that front/rear ambiguity, present in the photographs, is not present in the actual displayed 3-D image, where front appears at the front and rear appears at the rear. Photographs cannot convey the content of a true 3-D image any more than can a presentation on a flat CRT. Here, however, we have no choice but to document our work photographically with the depth dimension squeezed out. The photographs are *not* of the CRT of the SpaceGraph display but rather of the same display volume seen by the viewer. This distinction is apparent in Figures 3 and 4, which are photographs taken of the identical image but with a change in camera position. Image quality is much better in the real 3-D image than in the photographs.

Our first task was to create an image of an airplane, so that GDP, using it as one of its primitive display elements, could scale it, orient it, and position it to suit the immediate needs. Figure 1 shows the airplane model. It is sparse when shown at this magnification, but adequately dense when demagnified, using GDP and placed into a coordinate reference frame.

The IOS at the SAAC has a perspective presentation of the two trainees' planes. Figure 2 is a Xerox copy of a hard copy made from this IOS presentation. Figures 3 and 4 are *two views of one 3-D image* which depicts the same kind of pictorial information.

At this point it is important to observe that the information in the SAAC from which Figure 2 was created contains all of the relevant 3-space coordinates. To create Figure 2 therefore is a geometrical process of squeezing out one dimension to make it displayable on a flat surface. The information in the SpaceGraph display's computer from

which the image photographically represented by Figure 3 (or 4) was created is the same set of relevant 3-space coordinates. In a few words, both computers, i.e., the SAAC's and SpaceGraph's, started with the same information. This point must be emphasized, since it implies that a SpaceGraph display could be attached to the SAAC rather simply.

Figure 5 is a photographic representation of a 3-D image showing a plane executing the bombing run at the ASPT. The same positional information is shown in two views at the IOS of the ASPT, one a plan view and the other an elevation view. We believe that the single 3-D image not only communicates more simply, but that it lends itself to adding bomb trajectories, predictive vectors, error-from-prescribed-path information, history of path improvement, and other positional and attitudinal information, all *before* resorting to alphanumerics.

Figure 6 is a photograph of an image we created for training or "choreographing" formation flying. Confusion in the photograph is completely absent in the image, a fact which underscores (a) how inadequate flat surfaces are for these kinds of portrayals, and (b) how much information in the 3-D image is lost when one dimension is squeezed out.

As a game in the lounge (suggestion #54), it is exciting to imagine Figure 3 representing (in 2-D) what each combatant sees (in 3-D). The opponent could be the computer (much as one can play chess versus a computer), the instructor, or another student pilot. The "lesson" could be flight dynamics, energy maneuvering, aerial tactics, or radar intercepts. Missiles or cannon fire could be shown. Ground targets, landing fields, or carrier decks could be shown. This kind of outside-in view lends itself to a wide range of possibilities.

We have constructed no trial images specifically for landing practice but there are at least several kinds possible. In addition to simplistic outside-in images like that suggested by Figure 5, it might be profitable to show details of the correct landing pattern — the glideslope, range markers, gates, etc. Inside-out views are also worth investigating, although they raise new questions about showing scenery at great distances. One possibly attractive solution is to show scenery which lies beyond the back plane of the display volume as a 2-D picture on this back plane — just as stage sets show 3-D props on stage and a flat backdrop of what lies beyond.

Another class of images is that which forsakes realism and instead shows a goal, allowable error bounds, and the current state. A simple example is a landing approach: Imagine the goal to be a 3-D "bulls-eye." Error bounds above and below show glideslope bounds; error bounds right and left show line-up bounds; and error bounds fore and aft show velocity bounds. A 3-D cross-hair shows the current state of glideslope, line-up, and velocity. The error bounds naturally shrink as touchdown is approached. Notice that the three spatial dimensions of the display volume have been used in this example to show two dimensions of space and one of velocity. Numerous goal directed tasks lend themselves to this kind of presentation, but we have not pursued them yet, believing

that images portraying greater pictorial realism will be easier for new users to accept. (Also, there is a question of applicability at the IOS.) Nevertheless, we believe the possibilities here are at least as great as those in the photographs.

IV. PRIORITIES FOR FUTURE DEVELOPMENT

We originally proposed to create a priority-ordered list of desirable future developments. Accordingly, here is the list as motivated by our perception of the requirements for pilot training in general and for the IOS in particular.

1. Speed-up creation of display files: Adding motion to show airplanes flying requires much faster creation of display files than is currently possible. We believe the speed-up required is about 1000x, and it appears that the specificity of the application will make this possible, even in the presence of the unfavorable (for this application) computer architecture surrounding the present implementation of SpaceGraph.

2. Increase plotting speed: We believe this development to be important, since it will noticably improve the resolution of small airplane images. This development will be incorporated into the next generation of this display technology.

3. Automatic phase synchronization between mirror and CRT: This refinement over the current state-of-the-art is a prerequisite for an easy-to-use display device. It will be incorporated into the next generation of this display technology.

4. Mirror refinement: This refinement inevitably will take place as succeeding mirrors are built.

5. Increased display depth: This improvement would facilitate several of the promising application ideas disclosed herein. However it is not necessary. Increased depth can be achieved by refinements in the mirror design itself or by auxiliary optics. Both approaches are promising, although the latter approach is more straightforward.

6. Increased mirror and/or CRT size: The need for larger mirrors or CRTs has not been established. It is an application-dependent question. The applications suggested herein can be adequately served, at least at first, without major changes in geometry. Two possible exceptions: a wider CRT would help some applications, like those which portray migrating objects; and a smaller CRT/mirror combination might be advantageous for certain airborne applications.

7. Daylight-viewable display: Because most of the applications suggested herein can use a non-daylight-viewable display, this developmental priority appears low. But there are some applications which must have a daylight-viewable capability, and for the moment, these applications cannot be seriously contemplated. Daylight viewability seems feasible, but it would require a substantial developmental effort with no guarantee of success.

8. Phosphor optimization: This desirable task need not be undertaken as long as there are no serious problems with image brightness.

So far, there are not.

9. Addition of a machine-erected cursor to the image: For almost all of the applications discussed herein, this refinement is not necessary. However a cursor is indispensable for certain other applications, so that it will probably be developed anyway.

10. Add color: Color capability has been placed at the bottom of the priority list, since we are not convinced that color would materially improve any of the application ideas discussed in this report. Color is a difficult enhancement for SpaceGraph.

V. CONCLUSIONS

The proposal for the work done under this contract was witten in April 1978, at which time the SpaceGraph display was less capable than now, and application ideas in aviation had been limited to air traffic control. As direct results of this contract, we have learned much about the IOS, the SpaceGraph display is technically more mature, and several application ideas for the IOS and for pilot training have crystallized. In particular, we have identified specific IOS needs which could be directly met by the SpaceGraph display technology.

Both at the SAAC and at the ASPT, the IOS uses awkward (in our opinion) presentations for aircraft position. These presentations appear to be attempting exactly that which the SpaceGraph display does very well.

Beyond these clear-cut ways to use the new display resource at the IOS, we have begun to see a host of other possibly more important uses near the IOS. The one we regard with greatest immediate expectations is the realistic outside-in view of one or more aircraft which can be flown with realistic flight dynamics. The possibilities here for part-task pilot training seem remarkably broad, and considering the likely operating cost of such a device, say $18/hr*, remarkably inexpensive.

Also very promising is the exploitation of the third spatial dimension to create a new kind of "flight" director for multi-variable goal-oriented tasks, e.g., radar intercepts, air refueling, landing, ordnance delivery, etc. This class of use is not near-term, however, since even the basic human factor work has not yet been done.

Basic to any exploitation of the SpaceGraph display is having one and having that one with adequate performance. Currently one exists, and it is used by several different groups at BBN for very diverse purposes. Its performance is currently limited to showing static images. Although it could be reprogrammed to show simple moving images, like one or two aircraft, the next generation of this display technology will be much more suitable for this purpose.

*Assumptions: Capital cost of display plus host computer = $125,000.
Total operating cost = 2.5% of capital cost per month.
Usage rate = 40/hours/week.

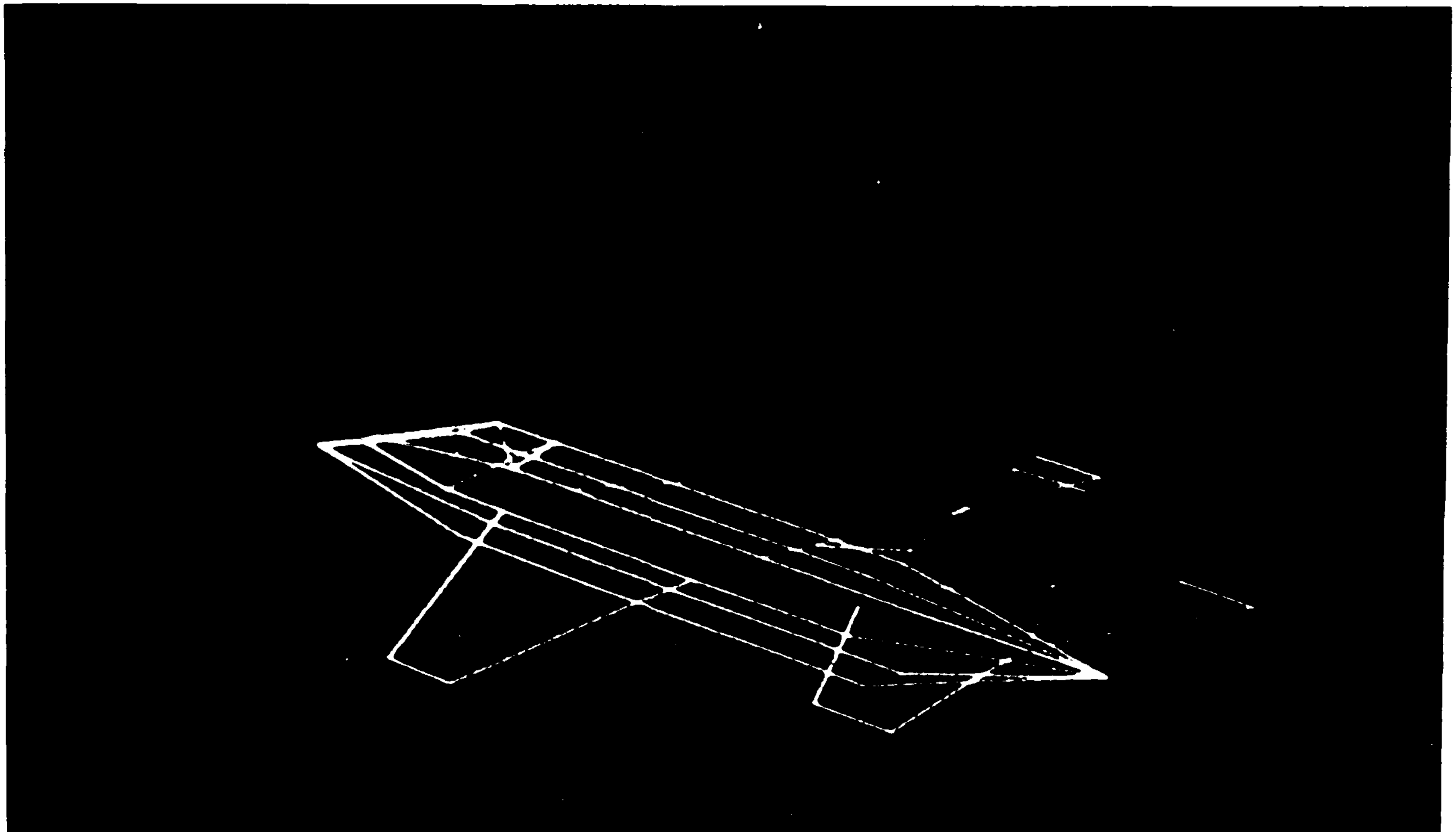

Figure 1. Photograph of a space-filling image showing airplane model to be used as a primitive display element in subsequent images. Transparency of the airplane image results in front-back confusion in the photograph but not in the actual 3-D image.

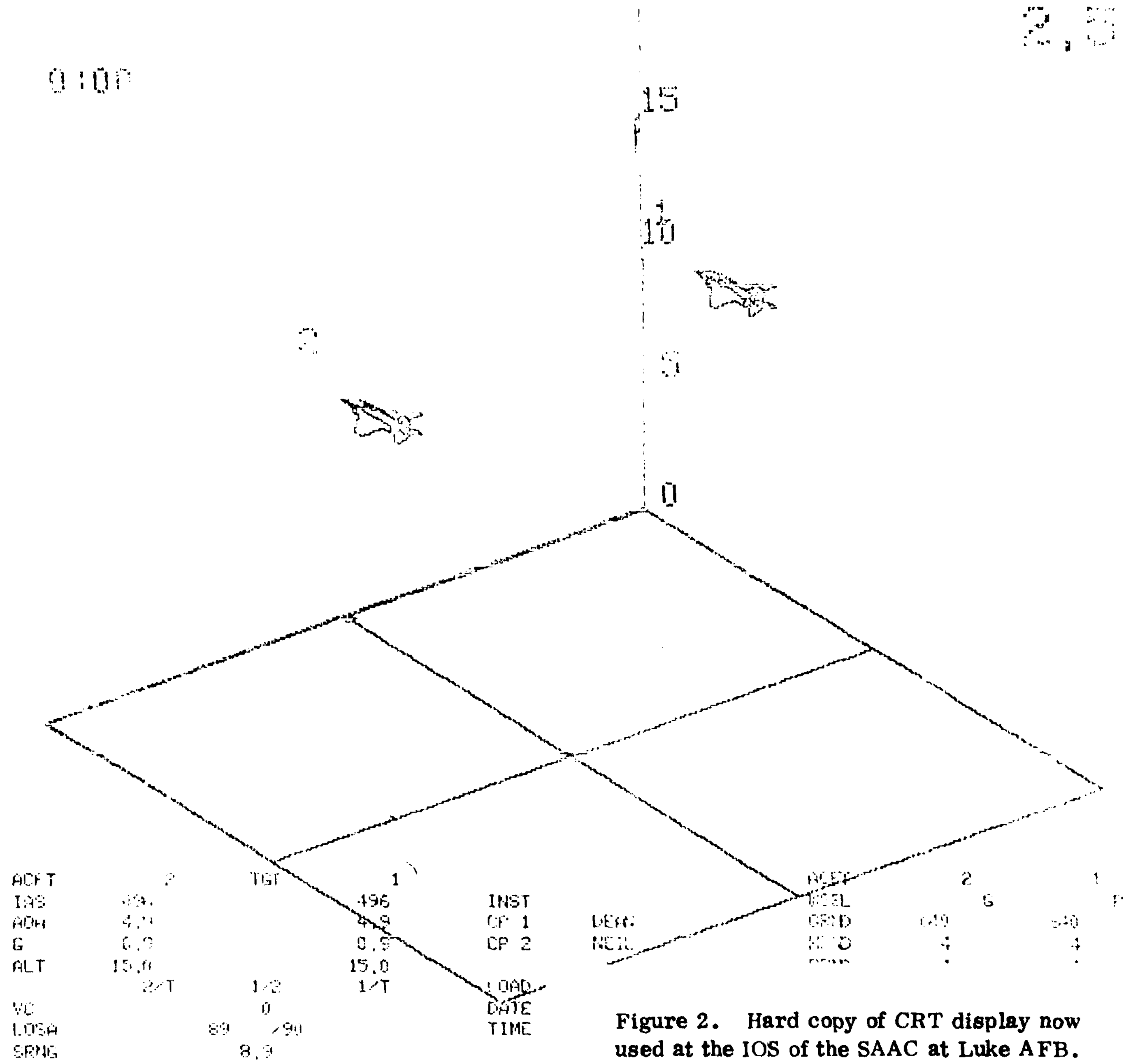

Figure 2. Hard copy of CRT display now used at the IOS of the SAAC at Luke AFB. The locations of the airplanes in space are no clearer in the actual flat display than in this flat reproduction of it.

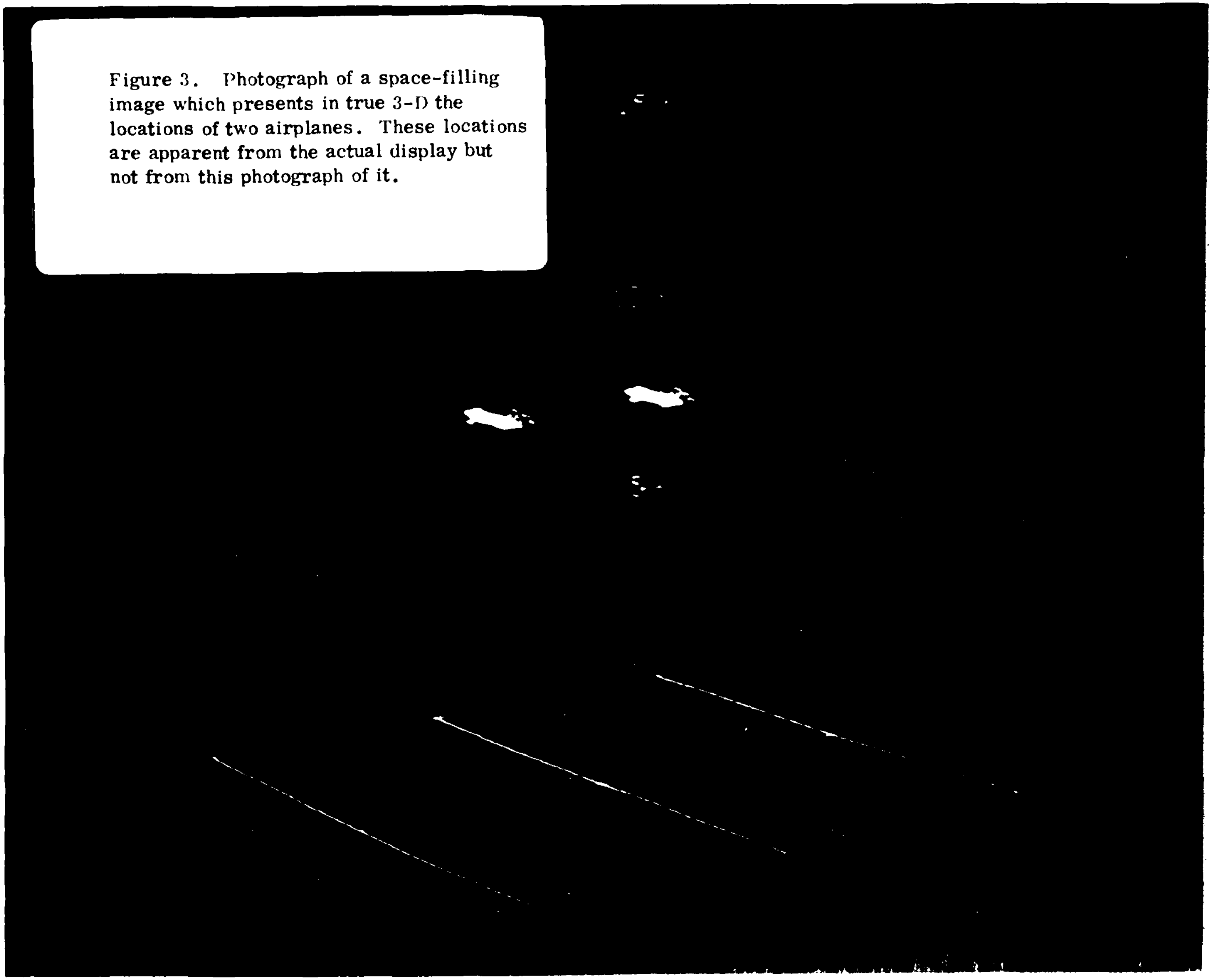

Figure 3. Photograph of a space-filling image which presents in true 3-D the locations of two airplanes. These locations are apparent from the actual display but not from this photograph of it.

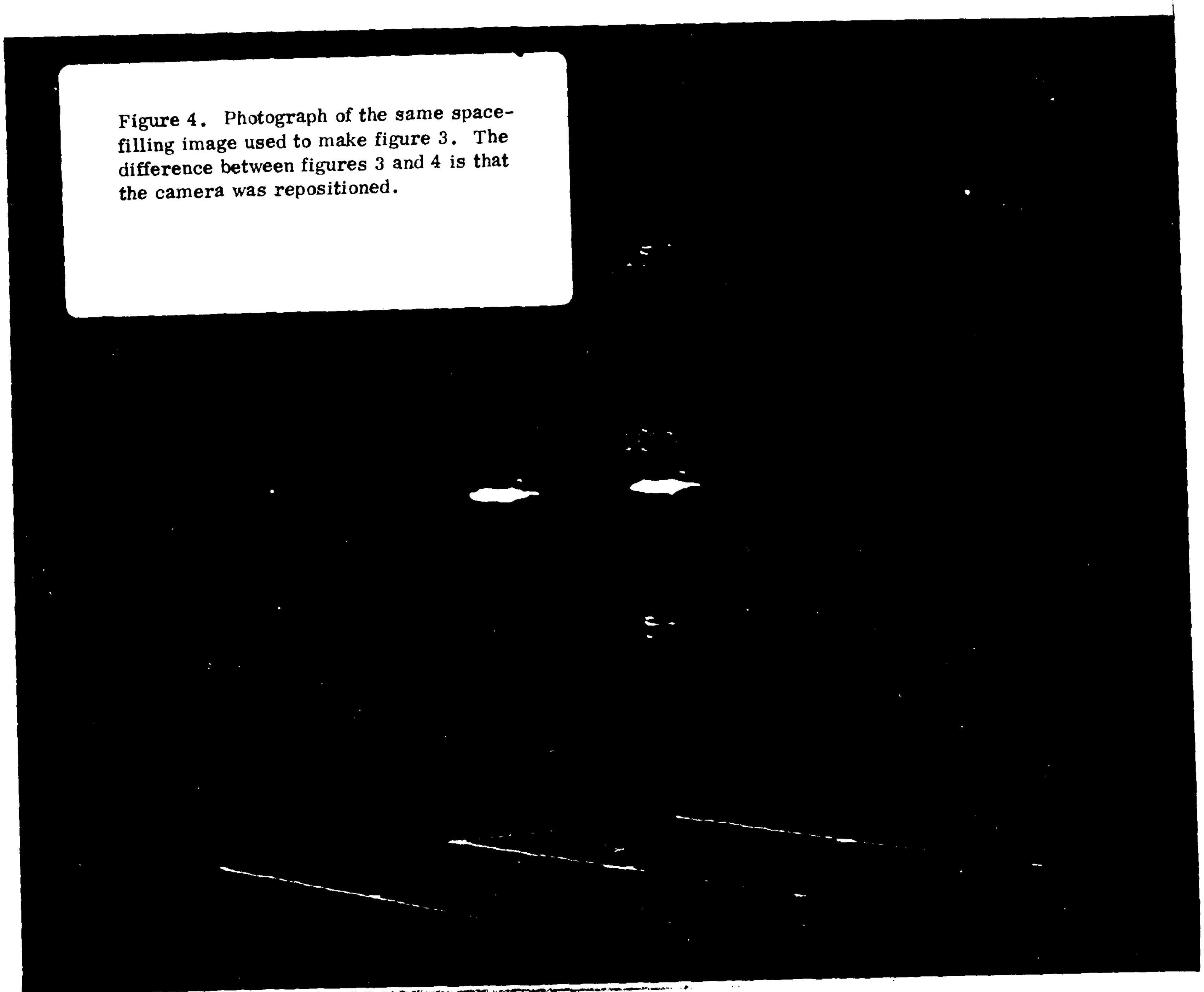

Figure 4. Photograph of the same space-filling image used to make figure 3. The difference between figures 3 and 4 is that the camera was repositioned.

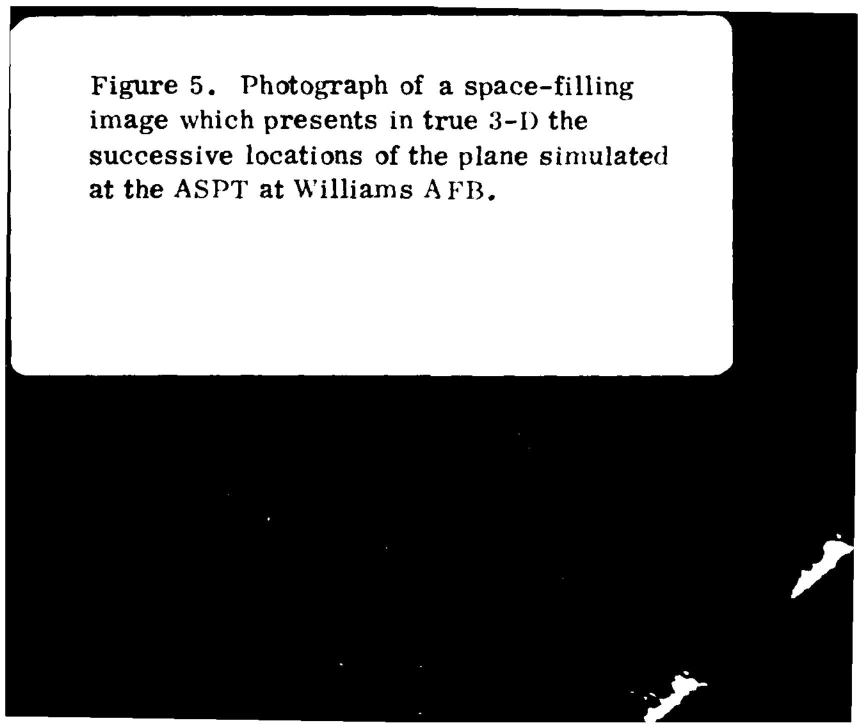

Figure 5. Photograph of a space-filling image which presents in true 3-D the successive locations of the plane simulated at the ASPT at Williams AFB.

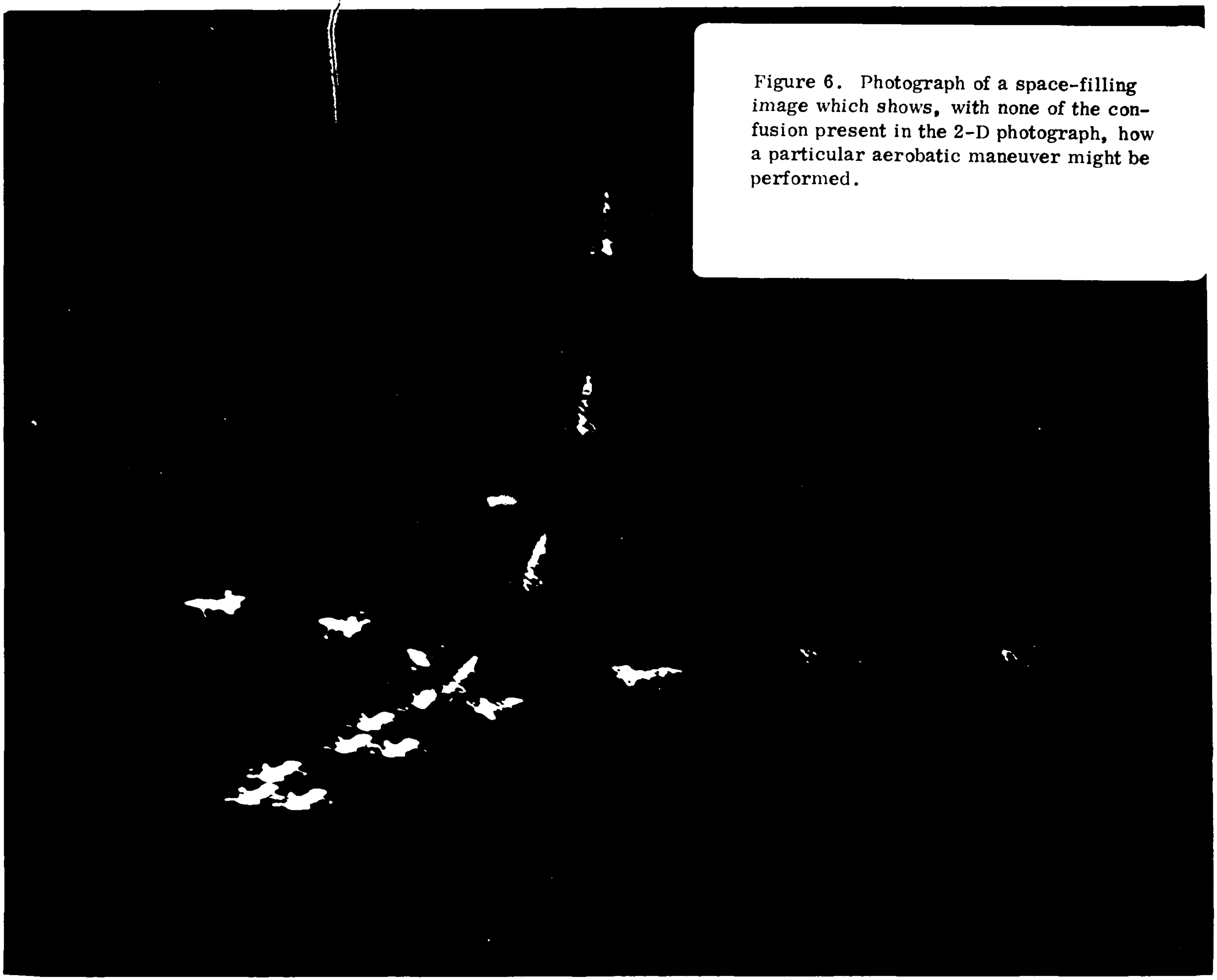

Figure 6. Photograph of a space-filling image which shows, with none of the confusion present in the 2-D photograph, how a particular aerobatic maneuver might be performed.

APPENDIX A

THE SPACEGRAPH DISPLAY: PRINCIPLES OF OPERATION AND APPLICATION

The SpaceGraph display provides space-filling images in a display volume rather than flat images on a display surface. Its use is logical and natural in 3-D applications now using flat displays, and its unique visual properties make possible altogether new applications. The purpose of this appendix is to explain how the SpaceGraph display works and how its capabilities can be exploited.

Principle of Operation — Visual Perceptual

Were it possible to oscillate a CRT along its axis, its phosphor screen would repeatedly sweep through a volume — the "display volume." Denoting screen coordinates by x and y and screen position in the volume by z(t), then an image element can be written at any (x, y, z) by writing it at (x, y) at the correct time. The image element's appearance will be satisfactory if

(a) it is rewritten regularly every 33 msec or more often ($\geq$30 Hz refresh rate)

(b) it is seen within a dark display volume

(c) it is not smeared in z by phosphor persistence.

Since it is not physically practical to oscillate a usefully large-screen CRT through a useful depth at a 30 Hz rate, the visual equivalent is used — oscillating an optical image of the phosphor screen. This alternative is physically practical, since the CRT can be stationary and the time-varying optics can take a very simple form.

Principle of Operation — Optics

As shown in Figure A-1, the simplest possibly suitable optical arrangement consists of an oscillating plane mirror. Because of the equality of image and object distance, the "leverage" of the plane mirror is 2, i.e., the image moves 2x as far as the mirror. For a good view of the image, the mirror must be large compared to the CRT. (Consider a 2-inch-square bathroom mirror: your image would be at the same place and have the same size as usual, but your view of the image would be severely restricted.) A plane mirror, therefore, must be large, must move through half of the desired image depth, and must oscillate at 30 Hz. This set of requirements does not admit a simple solution.

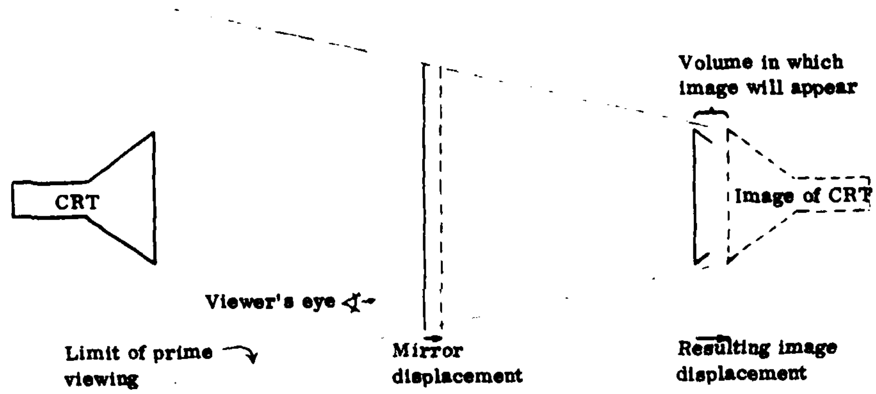

Figure A-1. In principle, a true 3-D display could be achieved using an oscillating plane mirror. Such a mirror is shown here moving from its closer (to the CRT) to its further position. The image of the CRT undergoes a corresponding excursion, but with twice the amplitude of motion. In practice, this scheme is essentially unrealizable.

Compared to the case of the flat mirror, if the mirror is forced to deform, it is possible to reduce the amplitude of mirror motion without sacrificing the amplitude of image motion. The price is constancy of magnification (always unity for the flat mirror). Figure A-2 shows the idea, exaggerating the mirror deformation for clarity.

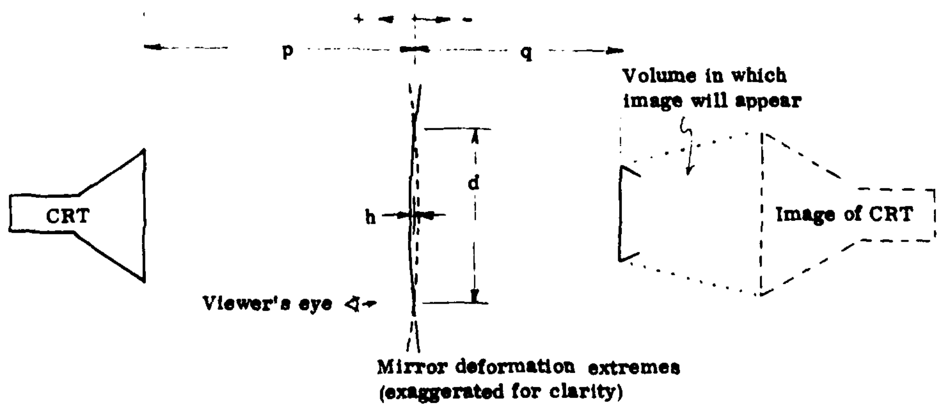

Figure A-2. In principle and in practice, a true 3-D display can be achieved by using a deforming mirror. The dimensions shown are used in the analysis below. Note that h is time-varying and, consequently, so is q. The solid and dotted depictions of the mirror give rise to the solid and dotted image positions respectively.

Here, the leverage is $\sim$85, as can be easily derived. L t distances measured to the left of the mirror be >0, and to the right <0.

p = object distance (fixed)

q(t) = image distance

h(t) = amplitude of mirror deflection at center

Assuming that the mirror is a spherical cap of radius r(t), or at least osculates with such a sphere, then it is known that

$$\frac{1}{p} + \frac{1}{q(t)} = \frac{2}{r(t)}$$

Simple geometry shows that*

$$r(t) = \frac{-1}{2h(t)}\left[\frac{d^2}{4} + h(t)^2\right],$$

and for the typical case wherein $|h_{max}| < 0.01d$,

$$r(t) = \frac{-d^2}{8h(t)}$$

Therefore,

$$q(t) = \frac{1}{-\frac{16h(t)}{d^2} - \frac{1}{p}}$$

For sinusoidal time dependence, where $h(t) = -|h_{max}| \sin \omega t$,

$$q(t) = \frac{1}{\frac{16|h_{max}|}{d^2}\sin \omega t - \frac{1}{p}}$$

For simplicity, it is convenient to let $A = \frac{16|h_{max}|}{d^2}$ and $B = \frac{1}{p}$, so that

$$q(t) = \frac{1}{A \sin \omega t - B}$$

Typical values are $|h_{max}| = 0.2$cm, d = 30cm, and p = 67cm, so $A = 3.56 \times 10^{-3}$ and $B = 1.49 \times 10^{-2}$.

For the convex extreme, $\sin \omega t = -1$ and $q_{convex} = -54.1$ cm.

For the concave extreme, $\sin \omega t = +1$ and $q_{concave} = -87.9$ cm.

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*Note: The minus sign arises becuase the sign convention of Figure A-2 requires that h(t) and r(t) always have opposite signs.

Thus the extremes of image position are 33.8 cm apart, a seeming violation of intuition considering that the mirror is moving only 0.4 cm (peak-to-peak) at its center. A potential disadvantage is that the image magnification, always given by $|q/p|$, is non-constant, varying from 1.3. (concave case) to 0.81 (convex case). However, a compensatory magnification on the CRT is easily implemented. The net inescapable price one pays is a display volume whose shape is the frustum of a rectangular pyramid (see Figure A-2).

Principle of Operation — Acoustical

The key pitfall in the design of a vibrating-mirror display is the inadvertent production of acoustic noise levels ranging from unpleasant to intolerable. Perceptually, the energy spectrum tells all. The ear is notably insensitive to frequencies at or below about 30 Hz. But 40 Hz is already more perceptible. Therefore it is important to keep the mirror motion as purely sinusoidal, at or below 30 Hz, as possible.

In the present design, two factors contribute to quietness. First, the mirror is designed as a mechanically resonant structure, with its fundamental resonant frequency (in the mode of interest — one circular node) at the desired frequency of operation. This arrangement is energy efficient and has clean sinusoidal behavior. Second, since the circular plate mirror vibrates with one concentric circular node, the edge of the front surface recedes as the center advances, and vice versa. This behavior reduces the alraady low radiation efficiency of the p'ate, whose diameter is only 3.5% of the wavelength of 30 Hz sound in air. Also, the visual effect of extending the mirror beyond its supporting hinge is extremely favorable, since the viewer has more freedom of head movement.

Principle of Operation — Mechanical

A vibratory structure whose deformed shapes at resonance are used optically and whose acoustical output is potentially malignant is a delicate design problem. For that reason, we resorted to a numerical model of the structure so as to iterate toward an optimal structure without many expensive construction/trial cycles.

Mechanical driving power for the plate is supplied by air pressure from an abutted woofer. Only a few watts are necessary, even for large plates (e.g., 40 cm), since the acoustic power radiated from the plate (and from the woofer cone's back surface) is very small, and the air coupling from woofer to resonant plate is efficient. Other drives are possible, since so little power is required and since sinusoidal behavior is the native behavior of a resonant structure. However, one must be very creative to match the reliability and low cost of a commercial woofer.

Principle of Application

The control of the x or y axis of a CRT is always "plot" or "sweep."

With "plot," the x-position (say) is set to a specific value, a value to be maintained until further notice. With "sweep," the x-position is caused to assume all legal values sequentially, usually in a linear motion. Since a raw CRT has two spatial axes, and each can operate in either of these two modes, there are four possibilities. Eliminating plot x/sweep y, since it is simply a symmetrical variant of sweep x/plot y, there are three essentially distinct graphics modes and all are in common use:

plot x/plot y, a "vector" or "directed beam" display device;

sweep x/plot y, a "time-base oscilloscope"; and

sweep x/sweep y, a "raster" display device.

If the <u>swept</u> spatial axis created by the moving mirror is called z (the brightness axis, sometimes called z, here will be called b), then a direct extension of the foregoing categories of possible graphics modes is as follows:

Mode A: plot x/plot y/sweep z

Mode B: sweep x/plot y/sweep z

Mode C: sweep x/sweep y/sweep z

This three-way distinction, illustrated in FIgure A-3 is pivotal in the following discussion.

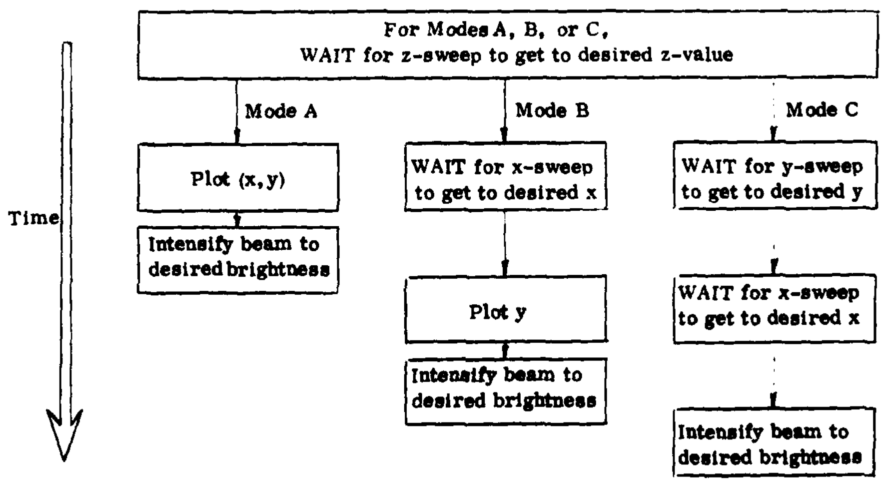

Figure A-3. To display a long image element, Modes A, B, and C involve increasing amounts of waiting.

The essential idea is that a volume element at (x, y, z) can be lit up to a specified brightness by one of three methods. The diagram makes clear that Mode C could entail a lot of waiting. Waiting is anathema to a refresh-type display, since there is a fixed interval of about 33 msec

in which to draw the image. Therefore, Mode C should be used only when there are image elements at most of the possible (x, y, z) locations.

For the same reason, Mode B should be used only when there are image elements at most of the possible (x, z) locations (there is no waiting for y).

It follows that Mode A is suited to sparse images.

Complementing this simple temporal argument is a simple spatial argument. A refresh-type display needs a memory out of which repeatedly flows the image information. For excellent spatial definition of a line drawing in Mode C, the image lattice should be at least (1000, 1000, 500). With 4 bits for brightness, the corresponding memory size is 2×10^9 bits and the corresponding data rate is 6×10^{10} bits/sec, putting this use of Mode C well into infeasibility. For excellent spatial definition of the same line drawing in Mode A, the image memory needs 28 bits per plotted value (12 for x, 12 for y, 4 for b) and, as will be shown, about 15000 values. There results a memory size of 420,000 bits and a data rate of 12×10^6 bits per second, wholly feasible numbers and with a better visual result in the bargain!

In summary, Modes A, B and C have complementary strengths and weaknesses. Mode A can provide excellent spatial resolution for a sparse image, while Mode C overcomes the sparseness limitation at the expense of spatial resolution. Mode B offers some virtues of A (resolution in y) and some of C (non-sparseness in x and z).

Use of Mode A

As z is swept, a sequence of (x, y) values is plotted on the CRT. The image memory only stores the sequence of (x, y) values, the "display file," since z is implicit in the order.

For purposes of creating the display file from a simple logical description of the desired image, the "raw picture," it is possible to imagine the raw picture as existing in some number N of depth zones. If N were small, each zone would have more in it, and the spatial resolution in z would suffer. The interesting question is how to size N. A simple argument, based solely on the above observation, leads inescapably to the conclution that N should be as large as possible. The largest possible value of N is such that each such depth zone contains the minimal possible image element — a dot. SpaceGraph's mode A works in that way, plotting one dot in each of many (thousands) depth zones.

Creating lines from dots means that the number of dots is the figure of merit rather than the more traditional figures of merit based on the number and/or lengths of long and short vectors. Since 10 dots, by observation, makes 1 cm of vector (in the display volume, not on the CRT), a conversion from 15000 dots to length of vector gives 1500 cm.

By visual, trials, this length of vector has been found to be sufficient for most applications.

Use of Mode B

Mode B essentially draws profiles and stacks them in depth. Terrain, for example as defined by contour lines, is easily converted to profiles and shown in mode B. In general, this mode is suited for any scalar function of two independent variables (e.g., altitude as a function of latitude and longitude). Using brightness in addition, one can show an additional scalar function (e.g., temperature and altitude as a function of latitude and longitude).

A different use of brightness is to hide hidden surfaces which otherwise would be visible. Hidden line elimination in the usual 2-D sense does not work here, since a line may or may not be hidden depending on the viewer's head movement. We have observed that an excellent expedient is to gradually (in space) dim out the line as it approaches a permanently hidden place.

Use of Mode C

Mode C naturally lends itself to the display of three-dimensional scalar fields — e.g., isotope concentration at each lattice point in a volume, or the density to X-rays for each volume element in a patient's head. The presentation provided by Mode C is (a) objective, (b) free of the artifacts of slicing, and (c) in a form admitting interaction with the viewer. Here, "objective" implies that two viewers see the same 3-D image, as opposed to seeing the same set of 2-D images and then independently making mental constructs to 3-D. "Free of the artifacts of slicing" implies that a solid sphere is displayed like a solid sphere, not like a set of solid disks. "In a form admitting interaction" implies that the viewer can reasonably ask to see and then get to see a revised presentation, for example, a spatial vignette excluding nonessential and possibly-obscuring foreground and background imagery. Interactivity distinguishes SpaceGraph images from holographic images.